



## Optimization of medical image compression of 3D Scalability by Volume of Interest Coding

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### ABSTRACT

Several compression for 3-D medical images have been proposed in the past year, some of which proved resolution and quality scalability up to lossless reconstruction. A novel 3-D scalable compression method for medical images with optimized volume of interest (VOI) coding were presented in this paper. The method is presented within the framework of interactive telemedicine applications, where different remote clients may access the compressed 3-D medical imaging data stored on a central server and request the transmission of different VOIs from an initial lossy to a final lossless representation. The VOI are decoded at the highest quality possible at any bit-rate, while allowing for the decoding of background information. The objective and subjective quality evaluation on various medical volumetric datasets shows that the proposed algorithms provide competitive lossy to lossless compression. The modified version of the embedded block coder with optimized truncation (modified EBCOT), tailored according to the characteristics of the data, encodes the residual data generated after prediction to provide resolution and quality scalability. The Digital watermarking is the process of embedding information into a digital signal which may be used to verify its authenticity or the identity of its owners, in the same manner as paper bearing a watermark for visible identification. Performance evaluations based on real 3-D medical imaging data showed that the proposed method achieves a higher reconstruction quality, in terms of the peak signal-to-noise ratio, than that achieved by 3D-JPEG2000 with VOI coding, when using the MAXSHIFT and general scaling-based methods.

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### Introduction

The 3-D Scalable Medical Image Compression with Optimized Volume of Interest Coding is proposed in this project. This method is presented within the framework of interactive telemedicine applications, where different remote clients may access the compressed 3-D medical imaging data stored on a central server and request the transmission of different VOIs from an initial lossy to a final lossless representation.

The main objective of this paper is to present a 3-D medical image compression method with scalability properties, by quality and resolution up to lossless reconstruction and optimized VOI coding at any bit-rate. Performance evaluations based on real 3-D medical imaging data showed that the proposed method achieves a higher reconstruction quality, in terms of the peak signal-to-noise ratio, than that achieved by 3D JPEG2000 with VOI coding, when using the MAXSHIFT and general scaling-based methods.

The method presented in this paper employs a 3D integer wavelet transform (3D-IWT) and a modified EBCOT with 3D contexts to compress the 3D medical imaging data into a layered bit-stream that is scalable by quality and resolution, up to lossless reconstruction. VOI coding capabilities are attained after compression by employing a bit-stream reordering procedure, which is based on a weighting model that

incorporates the position of the VOI and the mean energy of the wavelet coefficients.

With the wide pervasiveness of medical imaging applications in healthcare settings and the increased interest in telemedicine technologies, it has become essential to reduce both storage and transmission bandwidth requirements needed for archival and communication of related data, preferably by employing lossless compression methods. Furthermore, providing random access as well as resolution and quality scalability to the compressed data has become of great utility. Random access refers to the ability to decode any section of the compressed image without having to decode the entire data set. Resolution and quality scalability, on the other hand, refers to the ability to decode the compressed image at different resolution and quality levels, respectively. The latter is especially important in interactive telemedicine applications, where clients (e.g., radiologists or clinicians) with limited bandwidth connections using a remote image retrieval system may connect to a central server to access a specific region of a compressed 3-D data set, i.e., a volume of interest (VOI). The 3-D image is then transmitted progressively within the VOI from an initial lossy to a final lossless representation.

Several compression methods for 3-D medical images have been proposed in the literature, some of which provide resolution and quality scalability up to lossless reconstruction [1]-[6]. These methods are based on the discrete wavelet transform (DWT), whose inherent properties produce a bit-stream that is resolution-scalable.

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Quality scalability is then achieved by employing bit-plane based entropy coding algorithms that exploit the dependencies between the location and value of the wavelet coefficients, such as the embedded zerotree wavelet coding.

The method employs image compression technique that supports VOI coding based on the medical images which uses the 3-D sub-band block hierarchical partitioning (3D-SBHP), a highly scalable wavelet transform based entropy coding algorithm. A number of parameters that affect the effectiveness of VOI coding are studied, including the size of the VOI, the number of decomposition levels, and the target bit-rate. The authors also discussed an approach to optimize VOI decoding by assigning a decoding priority to the different wavelet coefficient bit-planes. In [12], the authors summarized the features of various methods for VOI coding, including the maximum shift (MAXSHIFT) and general scaling-based (GSB) methods supported by the JPEG2000 standard [14]. These particular methods scale up the coefficients associated with a VOI above the background coefficients, by a scaling value. The MAXSHIFT method employs a maximum scaling value so that VOI coefficients are completely decoded before any background coefficients. The GSB method, on the other hand, employs a lower scaling value so that VOI and background coefficients are decoded simultaneously. In [13], the authors presented a VOI coding method for volumetric images based on the GSB method and the shape-adaptive wavelet transform. The method extends the capabilities of the GSB method to 3-D images with arbitrarily-shaped VOIs and allows for coding partial background information in conjunction with the VOI. The main objective of this paper is to present a 3-D medical image compression method with 1) scalability properties, by quality and resolution up to lossless reconstruction and 2) optimized VOI coding at any bit-rate. We are particularly interested in interactive telemedicine applications, where different remote clients with limited bandwidth connections may request the transmission of different VOIs of the same compressed 3-D image stored on a central server. In this particular scenario, it is highly desirable to progressively transmit the different VOIs without the need to recode the entire 3-D image for each client's request. Furthermore, in order to improve the client's experience in visualizing the data remotely, it is also desirable to transmit the VOI at the highest quality possible at any bit-rate, in conjunction with a low quality version of the background, which is important in a contextual sense to help the client observe the position of the VOI within the original 3-D image [15]-[17]. In this work, the VOI is a cuboid defined in the spatial domain with possibly different values for the length, width and height. The method presented in this paper employs a 3-D integer wavelet transform (3D-IWT) and a modified EBCOT with 3-D contexts to compress the 3-D medical imaging data into a layered bit-stream that is scalable by quality and resolution, up to lossless reconstruction. VOI coding capabilities are attained after compression by employing a bit-stream reordering procedure, which is based on a weighting model that incorporates the position of the VOI and the mean energy of the wavelet coefficients. In order to attain optimized VOI coding at any bit-rate, the proposed method also employs after compression, an optimization technique that maximizes the reconstruction quality of the VOI, while allowing for the decoding of background information with peripherally increasing quality around the VOI. The proposed method is different from the method in [10], where the VOI coding procedure is tissue-based, the relative importance of a specific sub-band is empirically assigned, and the entropy coding of wavelet coefficients is performed using 2-D contexts. Our proposed method is also

different from the VOI coding method proposed in [11], where the background information is only decoded after the VOI is fully decoded, which prevents observing the position of the VOI within the original 3-D image. The proposed method also differs from the method in [13], where the scaling value of the VOI coefficients is empirically assigned and the shape information of the VOI must be encoded and transmitted, which may result in an increase in computational complexity as well as bit rate (due to shape encoding).

The novelties of the proposed method are threefold. First, our method employs the 3D-IWT in conjunction with a modified EBCOT with 3-D contexts to exploit redundancies between slices and improve the coding performance, while at the same time creating a layered bit-stream that is scalable by resolution and quality up to lossless reconstruction. Second, the bit-stream reordering procedure is performed after encoding, thus allowing for the decoding of any VOI without the need to recode the entire 3-D image. Third, the background information that is decoded in conjunction with the VOI allows for placement of the VOI into the context of the 3-D image and enhances the visualization of the data at any bit-rate.

We test the performance of the proposed method on various real 3-D medical images and compare it to 3D-JPEG2000 with VOI coding, using the MAXSHIFT and the GSB methods. Performance evaluation results show that, at various bit-rates, the proposed method achieves a higher reconstruction quality, in terms of the peak signal-to-noise ratio (PSNR), than those achieved by the MAXSHIFT and GSB methods.

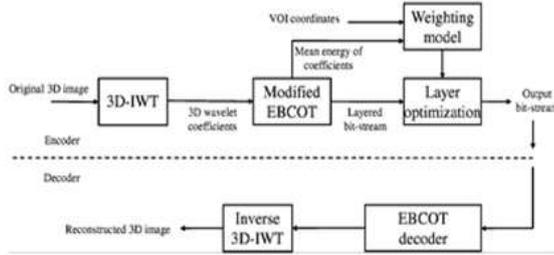
The remainder of the paper is organized as follows. In Section II, we describe the proposed compression method. In Section III, we present and discuss the experimental results. We give the concluding remarks in Section IV.

### Proposed Compression Method

The proposed compression method is depicted in Fig. 1. We first apply a 3D-IWT with dyadic decomposition to an input 3-D medical image. This transform maps integers to integers and allows for perfect invertibility with finite precision arithmetic, which is required for perfect reconstruction of a signal [18]. In this work, we employ the bi-orthogonal Le Gall 5/3 wavelet filter, implemented using the lifting step scheme [19]. Each level of decomposition,  $\ell$ , of the transform decomposes the 3-D image input into eight 3-D frequency sub-bands denoted as LLLr LLHr LHLr HLLr HLHr HHLr HHHr

The approximation low-pass sub-band, LLL, is a coarser version of the original 3-D image, whereas the other sub-bands represent the details of the image. The decomposition is iterated on the approximation low-pass sub-band.

We then group the wavelet coefficients into 3-D groups and compute the mean energy of each group. We encode each group of coefficients independently using a modified EBCOT with 3-D contexts to create a separate scalable layered bit-stream for each group. The coordinates of the VOI in the spatial domain, in conjunction with the information about the mean energy of the grouped coefficients, are then used in a weight assignment model to compute a weight for each group of coded wavelet coefficients. These weights are used to reorder the output bit-stream and create an optimized scalable layered bit-stream with VOI decoding capabilities and gradual increase in peripheral quality around the VOI. At the decoder side, the wavelet coefficients are obtained by applying the EBCOT decoder. Finally, an inverse 3D-IWT is applied to obtain the reconstructed 3-D image. The decoder can also truncate the received bit-stream to obtain a 3-D image at any bit-rate.



**Fig. 1. Block diagram of the proposed scalable lossless compression method. 3D-IWT: three-dimensional integer wavelet transform. EBCOT: embedded block coding with optimized truncation.**

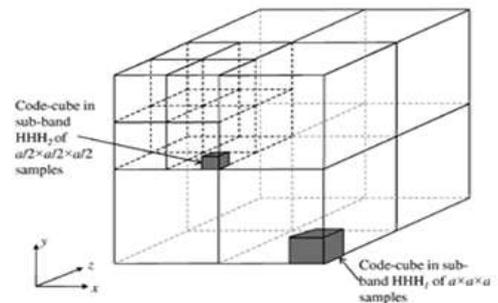
It is important to mention that the proposed method attains VOI decoding capabilities after the 3-D medical imaging data is coded. This is particularly advantageous in interactive telemedicine applications, where different clients may request different VOIs of the same compressed 3-D image stored on a central server. The server may then transmit different versions of the same compressed bit-stream by simply performing the bit-stream reordering procedure for each requested VOI, thus saving time in recoding the entire 3-D image for each client’s request. Moreover, if a client requests a different VOI while transmission of a compressed bit-stream is taking place, the server only needs to update the coefficient weights according to the newly requested VOI and reorder the untransmitted portion of bit-stream, which also saves time in recoding and retransmitting the entire 3-D image. Note that the bit-stream reordering procedure can take place before transmission since the decoder is capable of decoding any bit-stream regardless of the order it is transmitted (due to the fact that code-cubes are encoded independently). Alternatively, the bit-stream reordering procedure may also be performed at the client side once the image has been fully transmitted. In this particular scenario, the main advantage of the proposed method lies on saving time in recoding the entire 3-D image for different VOIs. There are three key techniques in the proposed compression method. The first is the modified EBCOT. The second is the weight assignment model. The last is the creation of an optimized scalable layered bit-stream. We will discuss them in the next subsections.

**Modified EBCOT**

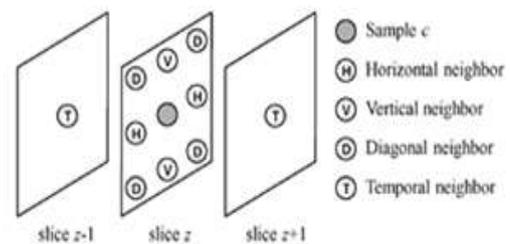
EBCOT is an entropy coding algorithm for 2-D wavelet-transformed images, which generates a bit-stream that is both resolution and quality scalable [9]. EBCOT partitions each sub-band in small group of samples, called code-blocks, and generates a separate scalable layered bit-stream for each code-block. The algorithm is based on context adaptive binary arithmetic coding and bit-plane coding, and employs four coding passes to code new information for a single sample in the current bit-plane. The coding passes are 1) zero coding (ZC), 2) run-length coding (RLC), 3) sign coding (SC), and 4) magnitude refinement (MR). A combination of the ZC and RLC passes encodes whether or not sample becomes significant in the current bit-plane. A sample is said to be significant in the current bit-plane if and only if. The significance of sample is coded using ten different context models (nine for the ZC pass and one for the RLC pass), which exploit the correlation between the significance of sample and that of its immediate neighbors. If sample becomes significant in the current bit-plane, the SC pass encodes the sign information of sample using five different context models. The MR pass uses three different context models to

encode the value of sample only if it is already significant in the current bit-plane. We may employ EBCOT to code the wavelet coefficients on a slice-by-slice basis. However, in our compression method, the input samples to the entropy coding algorithm are 3D-IWT wavelet coefficients rather than 2D-IWT wavelet coefficients. Therefore, coding 3D-IWT wavelet coefficients on a slice-by-slice basis makes EBCOT less efficient since the correlation between coefficients is not exploited in three dimensions. Consequently, a modified EBCOT algorithm is needed to overcome this problem, which we solve by partitioning each 3-D sub-band into small 3-D groups of samples (i.e., wavelet coefficients), which we call code-cubes, and coding each code-cube independently by using a modified EBCOT with 3-D contexts.

In this work, code-cubes are comprised of samples and describe a specific region of the 3-D image at a specific decomposition level. We employ a pyramid approach to define the size of code-cubes across the different decomposition levels. In this approach, a code-cube of size samples and position at decomposition level is related to a code cube of size samples and position at decomposition level, where is the first decomposition level. Fig. 2 shows the 3D-IWT sub-bands of a 3-D image after two levels of decomposition in all three dimensions with a single code-cube in sub-bands and .It can be seen that by employing a pyramid approach to define the size of code-cubes, it is possible to access any region of the 3-D image at any resolution, which is essential for VOI coding. In this work, we limit the code-cube dimension to be a power of 2, with



**Fig. 2. 3D-IWT sub-bands of a 3-D image after two levels of decomposition in all three dimensions with a single code-cube in sub-bandsand**



**Fig. 3. The immediate horizontal, vertical, diagonal and temporal neighbors of sample located in slices, slices**

We code each code-cube independently using a modified EBCOT with 3-D contexts that exploit inter-slice correlations. Coding wavelet coefficients by extending 2-D context modeling to 3-D has been extensively used to improve coding efficiency [1], [2], [20], [21]. Here, we propose a 3-D context model, based on the four coding passes previously discussed, that incorporates information from the immediate horizontal, vertical, diagonal and temporal neighbors of sample located in slices and as illustrated in Fig. 3.

During the ZC pass, we code whether or not sample becomes significant in the current bit-plane. As explained by Taubman in [9], the significance of sample is highly dependent upon the value of its immediate horizontal, vertical and diagonal neighbors. Here, in order to exploit interslice correlations, we also employ the information about the significance of the immediate temporal neighbors to code the significance of sample. Let  $n_h$  denote the number of significant horizontal neighbors, with  $n_v$  denote the number of significant vertical neighbors, with  $n_d$  denote the number of significant diagonal neighbors, with  $n_t$  denote the number of significant temporal neighbors, with  $n_{3D}$  denote the number of significant 3-D neighbors. The proposed 3-D context assignment for the ZC pass is summarized in Table I. Note that this 3-D context assignment emphasizes on the neighbors which are expected to present the strongest correlation in a particular sub-band. For example, we expect the strongest correlation amongst horizontally adjacent samples in sub-bands LLL, LLH, LHL, and LHH; therefore, the proposed 3-D context assignment emphasizes on horizontal neighbors for these sub-bands. For the SC pass, we expect that the sign information of sample exhibit some correlation with that of its temporal neighbors, in addition to the correlation exhibited with its vertical and horizontal neighbors, as explained in [9]. Therefore, in this pass, we employ the sign and significance information of the temporal, vertical and horizontal neighbors to code the sign information of sample. Let  $s$  denote the sign bit of sample, so that if  $s > 0$ ; otherwise,  $s < 0$ . Let  $n_h$  denote the sign information of the horizontal neighbors, with  $n_v$  if both horizontal neighbors are insignificant or both are significant with different sign, if at least one horizontal neighbor is positive, and if at least one horizontal neighbor is negative.

The proposed 3-D context assignment for the SC pass is summarized in Table II. Note that this 3-D context assignment exploits the fact that the distribution of given any particular neighborhood should be identical to the distribution of, given the dual neighborhood with the signs of all neighbors reversed. The binary valued symbol that is coded with respect to the corresponding context is  $s$ , where  $s$  is an auxiliary variable that indicates the sign prediction under a given context. For the MR pass, we also expect that the magnitude of sample exhibit some correlation with the magnitude of its immediate temporal neighbors. We thus employ the significance information of the immediate temporal neighbors, in addition to the significance information of the immediate horizontal and vertical neighbors, to code the magnitude of sample. Let  $n_h$  denote the total number of significant temporal, horizontal and vertical neighbors of sample, with  $n_t$  be a variable that transitions from 0 to 1 after sample  $s$  is found to be significant for the first time; i.e., after the MR pass is first applied to sample  $s$ . The proposed 3-D context assignment for the MR pass is summarized in Table III.

Note that for each coding pass, the coding engine maintains a look-up table in order to identify the probability model to be used by the adaptive arithmetic coder under each context.

#### Weight Assignment Model

The purpose of the weight assignment model is to enable the encoder to reorder the output bit-stream, so that the code-cubes that constitute the VOI are included earlier while allowing for gradual increase in peripheral quality around the VOI, under the constraint that the VOI is the main focal point. Techniques that allow gradual increase in peripheral quality around a focal point have been extensively used to improve image and video coding algorithms [22]-[25]. In the proposed compression method, we apply this technique to decode contextual background information with peripherally increasing quality around the VOI, which

in turn enhances the visualization of the data at any bit-rate. We achieve this by considering two main factors: 1) the proximity of a code-cube to the VOI and 2) the mean energy of a code-cube. The desired weight assignment for code-cube is a function of the form

We code each code-cube independently using a modified EBCOT with 3-D contexts that exploit inter-slice correlations. Coding wavelet coefficients by extending 2-D context modeling to 3-D has been extensively used to improve coding efficiency [1], [2], [20], [21]. Here, we propose a 3-D context model, based on the four coding passes previously discussed, that incorporates information from the immediate horizontal, vertical, diagonal and temporal neighbors of sample  $s$  located in slices and as illustrated in Fig. 3.

During the ZC pass, we code whether or not sample becomes significant in the current bit-plane. As explained by Taubman in [9], the significance of sample is highly dependent upon the value of its immediate horizontal, vertical and diagonal neighbors. Here, in order to exploit interslice correlations, we also employ the information about the significance of the immediate temporal neighbors to code the significance of sample. Let  $n_h$  denote the number of significant horizontal neighbors, with  $n_v$  denote the number of significant vertical neighbors, with  $n_d$  denote the number of significant diagonal neighbors, with  $n_t$  denote the number of significant temporal neighbors, with  $n_{3D}$  denote the number of significant 3-D neighbors. The proposed 3-D context assignment for the ZC pass is summarized in Table I. Note that this 3-D context assignment emphasizes on the neighbors which are expected to present the strongest correlation in a particular sub-band. For example, we expect the strongest correlation amongst horizontally adjacent samples in sub-bands LLL, LLH, LHL, and LHH; therefore, the proposed 3-D context assignment emphasizes on horizontal neighbors for these sub-bands. For the SC pass, we expect that the sign information of sample exhibit some correlation with that of its temporal neighbors, in addition to the correlation exhibited with its vertical and horizontal neighbors, as explained in [9]. Therefore, in this pass, we employ the sign and significance information of the temporal, vertical and horizontal neighbors, respectively. The proposed 3-D context assignment for the SC pass is summarized in Table II. Note that this 3-D context assignment exploits the fact that the distribution of given any particular neighborhood should be identical to the distribution of, given the dual neighborhood with the signs of all neighbors reversed. The binary valued symbol that is coded with respect to the corresponding context is  $s$ , where  $s$  is an auxiliary variable that indicates the sign prediction under a given context.

For the MR pass, we also expect that the magnitude of sample exhibit some correlation with the magnitude of its immediate temporal neighbors. We thus employ the significance information of the immediate temporal neighbors, in addition to the significance information of the immediate horizontal and vertical neighbors, to code the magnitude of sample. Let  $n_h$  denote the total number of significant temporal, horizontal and vertical neighbors of sample  $s$ , with  $n_t$  be a variable that transitions from 0 to 1 after sample  $s$  is found to be significant for the first time; i.e., after the MR pass is first applied to sample  $s$ . The proposed 3-D context assignment for the MR pass is summarized in Table III.

Note that for each coding pass, the coding engine maintains a look-up table in order to identify the probability model to be used by the adaptive arithmetic coder under each context.

#### Experimental results and discussion

We obtained two sets of experimental results. The first set evaluated the performance of the proposed method for VOI decoding at various bit-rates, including lossless reconstruction. The second set evaluated the effect of code-cube sizes on coding performance and size of the decoded VOI. We conclude this section with a discussion on the complexity of the proposed method.

#### Evaluation of VOI Decoding at Various Bit-Rates

Our test data set consisted of three 8-bit MRI and three 12-bit

CT sequences of various resolutions. We defined a single VOI comprising clinically relevant information in each of the test sequences. The characteristics of the 3-D test sequences, the corresponding VOI coordinates and code-cube sizes used for entropy coding are summarized in Table IV. Sequence 1 comprises MRI slices (sagittal view) of a human spinal cord; Sequence 2 comprises MRI slices (axial view) of a human head; and Sequence 3 comprises MRI slices (sagittal view) of a human knee. The test CT sequences comprise consecutive slices (axial view) of the "Visible Male" (Sequences 4 and 5) and "Visible

Woman" (Sequence 6) data sets maintained by the National Library of Medicine (NLM) [27]. In this work, the VOI is defined in the spatial domain by two sets of values,

#### Computational Complexity Considerations

We conclude our performance evaluation with a brief discussion regarding the complexity of the proposed compression method. Compared to 3D-JPEG2000 with VOI coding (MAXSHIFT and GSB methods), the proposed method presents a higher complexity at the encoder side due mainly to the bit-stream reordering procedure. This augmented complexity is a consequence of the calculation of the code-cube weights and the layer optimization technique, which needs to be performed each time a VOI is to be decoded. It is important to remember that, in the proposed method, the entropy coding process needs to be performed only once for a 3-D medical image, since the decoding of a VOI simply requires the reordering of the compressed bit-stream. As mentioned earlier, the calculation of the code-cube weights for a requested VOI simply requires the recomputation of two values for each code-cube. Moreover, the MSE required during the layer optimization technique is easily calculated from the information about the code-cube contributions into each quality layer, which is stored as header information during the coding process.

At the decoder side, the complexity of the proposed method is very similar of that of the MAXSHIFT method, since there is no need for the decoder to reorder the bit-stream prior to decoding. Compared to the GSB method, the decoding complexity of the proposed method is lower, since the GSB method requires the generation of a VOI mask prior to decoding.

Finally, it is important to remark that in the proposed method, all information needed to perform the bit-stream reordering procedure and layer optimization technique is stored and transmitted as header information. In the case of the test sequences evaluated in this work, this additional information represents a mere 0.04%-0.5% of the compressed bit-rate.

Digital watermarking is the process of embedding information into a digital signal which may be used to verify its authenticity or the identity of its owners, in the same manner as paper bearing a watermark for visible identification. In digital watermarking, the signal may be audio, pictures, or video. If the signal is copied, then the information also is carried in the copy. A signal may carry several different watermarks at the same time.

#### Conclusion

We presented a novel scalable 3-D medical image compression method with optimized VOI coding within the framework of interactive telemedicine applications. The method is based on a 3-D integer wavelet transform and a modified version of EBCOT that exploits correlations between wavelet coefficients in three dimensions and generates a scalable layered bit-stream. The method employs a bit-stream reordering procedure and an optimization technique to optimally encode any VOI at the highest quality possible in conjunction with contextual background information from a lossy to a lossless representation.

We demonstrated the two main novelties of the method; namely, the ability to decode any VOI from the compressed bit-stream without the need to recode the entire 3-D image; and the ability to enhance the visualization of the data at any bit-rate by including contextual background information with peripherally increasing quality around the VOI. We evaluated the performance of the proposed method on real 8-bit and 12-bit 3-D medical images of various resolutions. We demonstrated that the proposed method achieves higher reconstruction qualities than those achieved by 3D-JPEG2000 with VOI coding at a variety of bit-rates. We also demonstrated that the proposed method attains lossless compression ratios comparable to those attained by 3D-JPEG2000 with VOI coding. Finally, we studied the effect on coding performance and VOI decoding capabilities of the proposed method with different coding parameters. If the signal is copied for water marking, then the information also is carried in the copy. A signal may carry several different watermarks at the same time.

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